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Synergistic Effects of Steel and Polypropylene Fibers on the Mechanical Strength and Electrical Resistivity of Geopolymer Concrete: An Experimental and Machine Learning Study

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ABSTRACT

This study investigates the effects of steel, polypropylene (PP), and hybrid steel–PP fibers on the mechanical and electrical performance of geopolymer concrete activated with a 12 M sodium hydroxide solution. An experimental database comprising 81 observations was developed by considering different fiber systems, fiber dosages ranging from 0 to 2.0% by volume, and curing ages of 3, 28, and 90 days. Compressive strength, tensile strength, and electrical resistivity were evaluated to assess the combined structural and functional behavior of the developed geopolymer composites. The results demonstrated that both curing age and fiber dosage significantly enhanced the mechanical performance of geopolymer concrete. The highest compressive and tensile strengths, equal to 79.13 MPa and 7.15 MPa, respectively, were achieved by the steel-fiber mixture containing 2.0% fiber at 90 days. Steel fibers provided superior mechanical performance because of their high stiffness and crack-bridging capability, whereas polypropylene fibers produced considerably higher electrical resistivity because of their insulating nature. Hybrid steel–PP mixtures exhibited intermediate behavior and provided balanced mechanical and electrical performance. Machine-learning regression models were developed using fiber type, fiber dosage, and curing age as input variables. The models demonstrated high predictive capability, achieving R^2 values of approximately 0.98 for compressive strength, 0.96 for tensile strength, and 0.97 for electrical resistivity. The findings confirm the effectiveness of integrating experimental investigation with interpretable machine-learning techniques for predicting and optimizing geopolymer concrete performance.

Keywords: Geopolymer concrete; hybrid fiber reinforcement; polypropylene fiber; mechanical performance; interpretable machine learning

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1. INTRODUCTION

The development of sustainable and low-carbon cementitious materials has become one of the major research priorities in modern construction engineering because of the high

environmental impact associated with ordinary Portland cement (OPC) production. Geopolymer concrete has emerged as a promising alternative to OPC-based concrete because aluminosilicate-rich

precursors such as fly ash, slag, and metakaolin can react with alkaline activators to form hardened inorganic polymeric binder networks with favorable mechanical, durability, and environmental properties [1,2]. Compared with conventional cementitious systems, geopolymers concrete has been reported to exhibit lower carbon emissions, improved resistance to chemical attack, reduced chloride penetration, and enhanced long-term durability [3–5]. The engineering performance of geopolymer concrete is strongly influenced by several factors, including precursor composition, activator concentration, alkaline-solution chemistry, aggregate characteristics, curing regime, and the incorporation of reinforcing fibers [6–9].

Despite its environmental and technical advantages, geopolymer concrete often exhibits brittle behavior and limited tensile resistance, particularly under tensile, flexural, and impact loading conditions. Fiber reinforcement is therefore widely introduced to improve crack control, tensile strength, ductility, post-cracking response, and energy absorption capacity [10–15]. Previous studies have demonstrated that steel fibers are highly effective in enhancing the mechanical performance of geopolymer composites because of their high elastic modulus, strong interfacial bonding, and superior crack-bridging capability [14,15]. The incorporation of recycled or industrial steel fibers has also been shown to improve post-cracking behavior while simultaneously contributing to sustainable material development [16].

Polypropylene (PP) fibers exhibit different characteristics compared with steel fibers. Polypropylene fibers are lightweight, chemically stable, corrosion resistant, and electrically nonconductive. They are particularly effective in controlling plastic shrinkage cracking and improving crack distribution within cementitious matrices [12–17]. However, because of their relatively low stiffness and elastic modulus, polypropylene fibers generally contribute less to compressive and tensile strength enhancement than steel fibers [15–18]. Recent studies have suggested that hybrid fiber systems combining steel and polypropylene fibers may provide synergistic improvements by simultaneously enhancing strength, ductility, crack resistance, and durability-related properties [19–21]. In addition to conventional mechanical properties, electrical resistivity has gained increasing attention as a nondestructive durability-related indicator for

cementitious materials. Electrical resistivity is closely associated with ionic mobility, pore connectivity, moisture transport, and corrosion susceptibility [22–25]. Higher resistivity generally indicates lower ionic transport and reduced permeability, although the measured response is strongly influenced by moisture condition, pore-solution chemistry, saturation degree, conductive inclusions, and reinforcement type [24–26]. In fiber-reinforced geopolymer concrete, steel fibers may significantly reduce electrical resistivity because of their conductive nature, whereas polypropylene fibers may increase resistivity because of their insulating characteristics. Consequently, the simultaneous evaluation of mechanical performance and electrical resistivity is essential for performance-based mixture design and multifunctional material optimization.

In recent years, machine-learning techniques have become increasingly important for predicting the properties of cementitious materials because experimental responses are frequently governed by nonlinear and coupled interactions among multiple variables. Artificial intelligence and ensemble-learning approaches have been successfully applied to predict compressive strength, tensile behavior, workability, and durability-related properties of concrete and geopolymer composites [27]. Regression-based algorithms such as Random Forest, Gradient Boosting, and Support Vector Regression have demonstrated strong predictive capability when appropriate experimental datasets are available [28,29]. Nevertheless, machine-learning models developed from limited experimental datasets must be interpreted carefully, particularly when important variables such as activator molarity or precursor composition remain constant. Under such conditions, machine learning should be considered an interpretable supporting tool rather than a universal design model [30].

The present study investigates the effects of steel fibers, polypropylene fibers, and hybrid steel–polypropylene fiber systems on the compressive strength, tensile strength, and electrical resistivity of geopolymer concrete activated with a 12 M sodium hydroxide solution. The study integrates experimental investigation with interpretable machine-learning analysis to evaluate both structural and functional performance. The primary objectives are to: quantify the influence of fiber type, fiber dosage, hybridization strategy, and curing age on

mechanical and electrical properties; identify the contrasting roles of steel and polypropylene fibers in strength development and electrical transport behavior; and assess the capability of regression-

based machine-learning models to capture and predict the observed trends within the investigated experimental range.

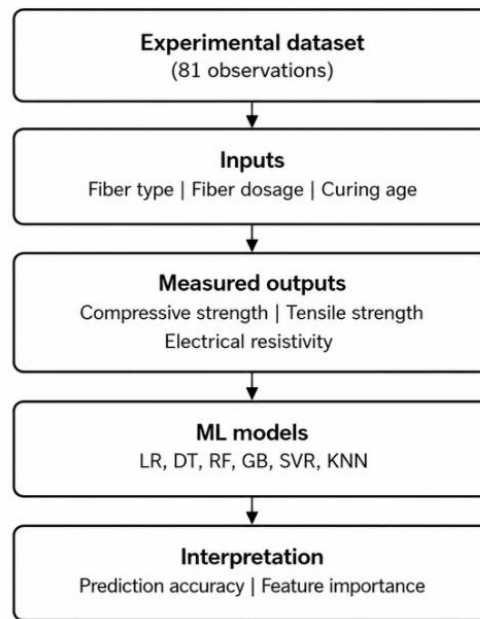


Figure 1. Experimental and machine-learning workflow used in the study

2. METHODOLOGY

The experimental program consisted of 81 observations designed to evaluate the influence of fiber type, fiber dosage, hybrid fiber combinations, and curing age on the mechanical and electrical performance of geopolymer concrete. The investigated variables included fiber type, fiber dosage, curing age, sodium hydroxide molarity, compressive strength, tensile strength, and electrical resistivity. Three fiber systems were considered: steel fibers, polypropylene (PP) fibers, and hybrid steel–polypropylene fiber mixtures. Fiber dosage varied from 0 to 2.0% by volume at intervals of 0.25%, resulting in dosage levels of 0, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00%. For the hybrid mixtures, the total fiber dosage was maintained constant while steel and polypropylene fibers were incorporated in equal volumetric proportions. The specimens were tested after curing periods of 3, 28, and 90 days. The alkaline activator consisted of a 12 M sodium hydroxide (NaOH) solution combined with sodium silicate solution. Since the NaOH molarity remained constant throughout the experimental program, it was not included as an input parameter in the statistical or machine-learning analysis.

The geopolymer concrete mixtures were prepared using Class F fly ash and ground granulated blast

furnace slag (GGBFS) as aluminosilicate precursors with a fly ash-to-GGBFS ratio of 70:30 by mass. The total binder content was 450 kg/m³. Fine and coarse aggregate contents were maintained at 650 kg/m³ and 1050 kg/m³, respectively. The sodium silicate-to-sodium hydroxide ratio was fixed at 2.5 by mass, while the alkaline liquid-to-binder ratio was maintained at 0.45. Additional water corresponding to 0.05–0.08 of the binder mass was incorporated to improve workability. A polycarboxylate-based superplasticizer dosage of 1.0% by binder mass was used in all mixtures.

The steel fibers had a length of 30 mm, a diameter of 0.50 mm, and an aspect ratio of 60. The polypropylene fibers had a length of 12 mm, a diameter ranging from 18 to 25 μm, and an aspect ratio of approximately 480–670. In the hybrid mixtures, both fiber types were blended uniformly to improve crack resistance while balancing mechanical strength and electrical resistivity characteristics. Control mixtures without fibers were included as reference specimens.

Compressive-strength tests were conducted on 100 × 100 × 100 mm cube specimens in accordance with ASTM C39 (or BS EN 12390-3 equivalent procedures). Splitting tensile-strength tests were performed on 100 × 200 mm cylindrical specimens

following ASTM C496 (or BS EN 12390-6 equivalent procedures). Electrical resistivity measurements were conducted using the Wenner four-probe method in accordance with AASHTO T358. All specimens were cured for 24 h at room temperature before being stored under sealed ambient curing conditions at a temperature of 23 ± 2 °C and relative humidity of $60 \pm 5\%$ until the testing age.

The compressive loading rate was maintained at approximately 0.25 MPa/s, while the splitting tensile loading rate ranged between 0.7 and 1.4 MPa/min. For each mixture and testing age, three replicate specimens were tested, and the reported values correspond to the mean results. Standard deviation was used to quantify the statistical dispersion of replicate measurements.

The available experimental dataset includes compressive strength, tensile strength, and electrical resistivity measurements. Although the broader research program was intended to include flexural-strength testing, flexural data were not available at the time of analysis. Therefore, the present study focuses quantitatively on compressive strength, tensile strength, and electrical resistivity.

Statistical analysis was carried out using descriptive statistics, group comparisons, and Pearson

correlation coefficients. Fiber type was encoded numerically for machine-learning analysis, with steel fiber represented by 1, polypropylene fiber represented by 0, and hybrid fiber mixtures represented by 2. The machine-learning analysis considered fiber type, fiber dosage, and curing age as input variables. Separate predictive models were developed for compressive strength, tensile strength, and electrical resistivity. The investigated algorithms included Linear Regression (LR), Decision Tree (DT), Random Forest (RF), Gradient Boosting (GB), Support Vector Regression (SVR), and K-Nearest Neighbors Regression (KNN).

Because the dataset contained only 81 observations, model performance was evaluated using five-fold cross-validation rather than relying solely on a single train–test split. Model performance was assessed using the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE). Feature-importance analysis was performed using tree-based learning models, with particular emphasis on the Gradient Boosting algorithm because of its capability to capture nonlinear relationships while remaining relatively interpretable.

Table 1. Experimental variables and measured responses.

Item	value
Precursor	Class F fly ash + GGBFS
Fly ash/GGBFS	70:30 by mass
Binder content	450 kg/m ³
Fine aggregate	650 kg/m ³
Coarse aggregate	1050 kg/m ³
NaOH molarity	12 M
Na ₂ SiO ₃ /NaOH ratio	2.5 by mass
Alkaline liquid/binder ratio	0.45
Extra water/binder ratio	0.05–0.08, only for workability
Superplasticizer	1.0% of binder
Steel fiber length	30 mm
Steel fiber diameter	0.50 mm
Steel fiber aspect ratio	60
PP fiber length	12 mm
PP fiber diameter	18–25 µm
PP fiber aspect ratio	about 480–670
Fiber dosage	0, 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00% by volume
Compressive specimens	100 × 100 × 100 mm cubes
Tensile specimens	100 × 200 mm cylinders
Resistivity specimens	100 × 200 mm cylinders or 100 mm cubes
Curing	24 h at room temperature, then sealed/ambient curing

Curing temperature	23 ± 2 °C
Relative humidity	60 ± 5%
Test ages	3, 28, 90 days
Compressive standard	ASTM C39 or BS EN 12390-3
Splitting tensile standard	ASTM C496 or BS EN 12390-6
Resistivity standard	AASHTO T358 / Wenner four-probe
Compression loading rate	0.25 MPa/s
Splitting tensile loading rate	0.7–1.4 MPa/min
Replicates	3 specimens per mixture per age
Reported result	Mean ± standard deviation

3. RESULTS AND DISCUSSION

The experimental results demonstrated significant variations in mechanical and electrical properties across the investigated fiber systems, fiber dosages, and curing ages. Compressive strength ranged from 31.06 to 79.13 MPa, with an average value of 52.54 MPa and a standard deviation of 11.06 MPa. Tensile strength varied between 3.02 and 7.15 MPa, with a mean value of 4.67 MPa and a standard deviation of 0.97 MPa. Electrical resistivity ranged from 14.84 to 29.97 kΩ·cm, with an average value of 21.98 kΩ·cm

and a standard deviation of 4.37 kΩ·cm. The highest compressive and tensile strengths were achieved by the steel-fiber mixture containing 2.0% fiber at 90 days, whereas the highest electrical resistivity was observed in the polypropylene-fiber mixture containing 1.75% fiber at 90 days. Hybrid steel–polypropylene mixtures exhibited intermediate behavior, combining enhanced mechanical strength with moderate electrical resistivity.

Table 2. Overall statistical summary of measured properties

Property	Minimum	Maximum	Mean	Standard deviation
Compressive strength (MPa)	31.06	79.13	52.54	11.06
Tensile strength (MPa)	3.02	7.15	4.67	0.97
Electrical resistivity (kΩ·cm)	14.84	29.97	21.98	4.37

Curing age had a pronounced influence on all measured properties. The average compressive strength increased from 44.41 MPa at 3 days to 49.39 MPa at 28 days and further to 63.83 MPa at 90 days. Similarly, tensile strength increased from 4.19 MPa at 3 days to 4.52 MPa at 28 days and reached 5.29 MPa at 90 days. Electrical resistivity also increased with curing age, rising from 20.61 kΩ·cm at 3 days to 21.59 kΩ·cm at 28 days and 23.75 kΩ·cm at 90 days. These trends indicate continued

geopolymerization reactions and progressive refinement of the internal microstructure beyond 28 days of curing.

The Pearson correlation coefficient between curing age and compressive strength was 0.751, indicating that curing age was the most influential linear parameter governing compressive-strength development. The corresponding correlations between curing age and tensile strength and electrical resistivity were 0.483 and 0.303, respectively.

Table 3. Mean measured properties by curing age

Curing age	Compressive strength (MPa)	Tensile strength (MPa)	Electrical resistivity (kΩ·cm)
3 days	44.41	4.19	20.61
28 days	49.39	4.52	21.59
90 days	63.83	5.29	23.75

Fiber type significantly affected the balance between mechanical performance and electrical transport behavior. Steel-fiber mixtures produced the highest average compressive and tensile strengths, with mean values of 54.94 MPa and 4.99 MPa, respectively. Polypropylene-fiber mixtures exhibited lower average compressive and tensile strengths of 50.14 MPa and 4.34 MPa, respectively. The superior mechanical performance of steel fibers can be attributed to their higher stiffness, stronger interfacial bond with the matrix, and enhanced crack-bridging capacity. Hybrid steel–polypropylene mixtures exhibited intermediate mechanical performance because the steel fibers contributed to load transfer while the polypropylene fibers improved crack distribution and ductility.

In contrast, electrical resistivity exhibited the opposite trend. Polypropylene-fiber mixtures showed the highest average electrical resistivity, reaching 25.75 kΩ·cm, whereas steel-fiber mixtures exhibited a considerably lower average resistivity of 18.22 kΩ·cm. Hybrid mixtures produced intermediate resistivity values because the electrically conductive steel fibers partially reduced the insulating effect of polypropylene fibers. The correlation coefficient between the steel-fiber indicator and electrical resistivity was -0.869 , demonstrating the strong influence of steel fibers in reducing the bulk resistivity of the geopolymer composite.

Table 4. Mean measured properties by fiber type

Fiber type	Compressive strength (MPa)	Tensile strength (MPa)	Electrical resistivity (kΩ·cm)
Steel fiber	54.94	4.99	18.22
Polypropylene fiber	50.14	4.34	25.75
Hybrid steel–PP fiber	52.68	4.71	21.84

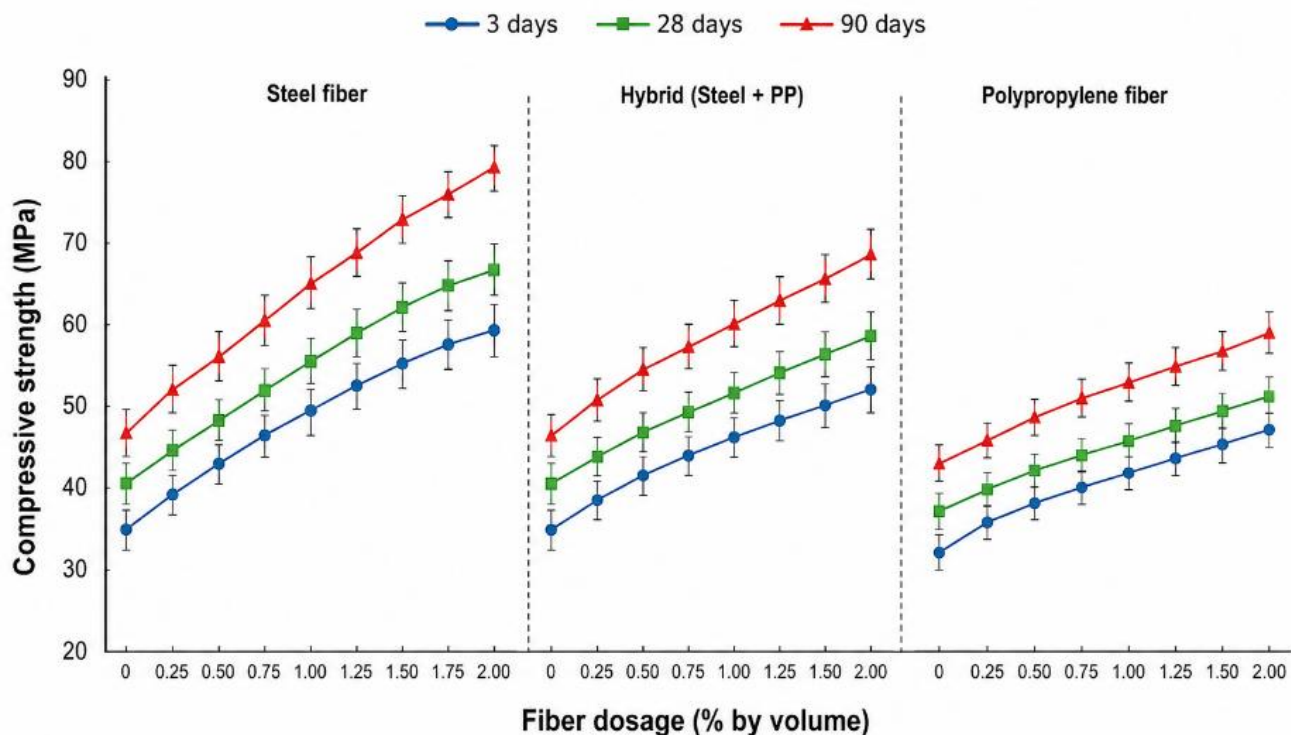


Figure 2. Compressive strength development as a function of fiber dosage, fiber type, and curing age

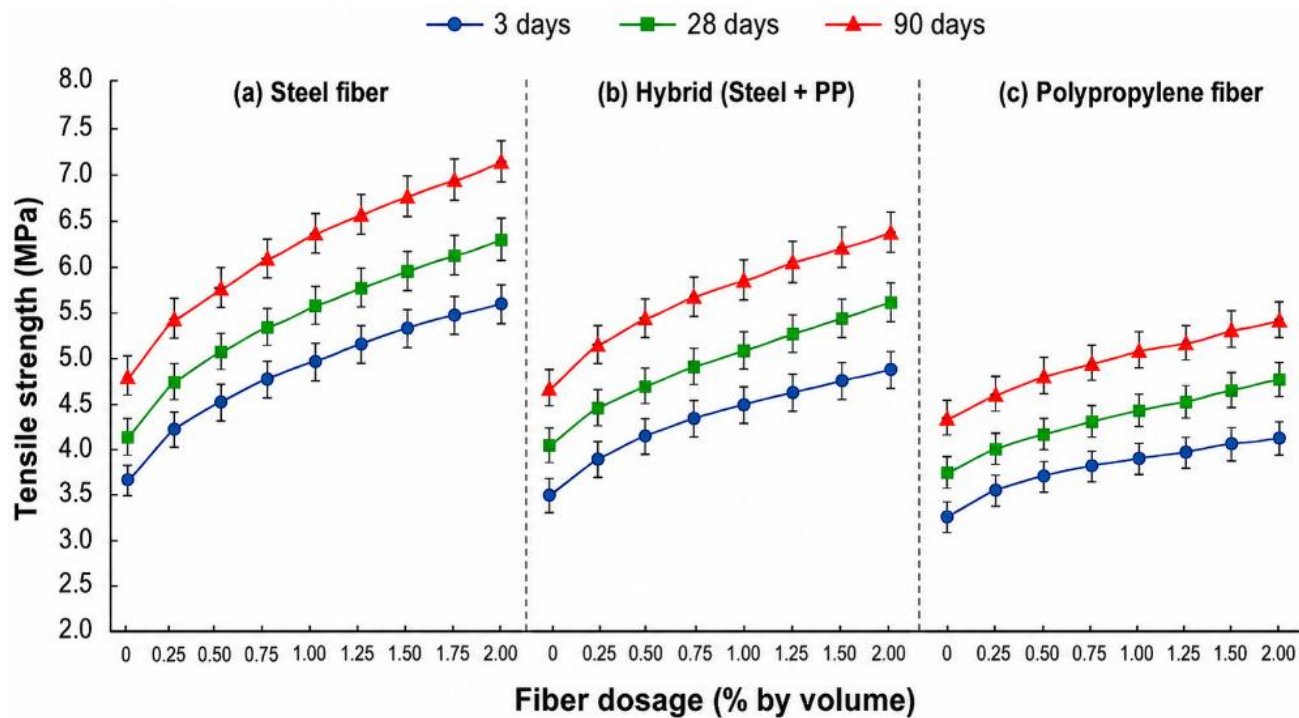


Figure 3. Tensile strength development as a function of fiber dosage, fiber type, and curing age

Electrical resistivity exhibited behavior different from that of mechanical strength. In steel-fiber mixtures, mean resistivity decreased from approximately $20.81 \text{ k}\Omega\cdot\text{cm}$ at 0% fiber to $15.43 \text{ k}\Omega\cdot\text{cm}$ at 2.0% fiber because conductive steel fibers created electrically conductive pathways within the geopolymer matrix. In contrast, polypropylene-fiber mixtures showed increasing resistivity with increasing fiber dosage, rising from approximately $23.80 \text{ k}\Omega\cdot\text{cm}$ at 0% fiber to $27.82 \text{ k}\Omega\cdot\text{cm}$ at 2.0% fiber. This increase is attributed to the nonconductive nature of polypropylene fibers, which interrupted conductive pore pathways and increased electrical resistance.

Hybrid fiber mixtures exhibited intermediate resistivity values because the conductive influence of steel fibers was partially offset by the insulating behavior of polypropylene fibers. These findings demonstrate that the selection of fiber type strongly

influences the balance between mechanical performance and electrical transport properties. Steel fibers are more suitable when high mechanical strength is required, whereas polypropylene fibers are advantageous when higher electrical resistivity and durability-related performance are prioritized. Overall, the results demonstrate that the performance of fiber-reinforced geopolymer concrete is governed by coupled effects of fiber type, fiber dosage, and curing age. The highest mechanical performance was achieved in mixtures containing high steel-fiber dosages combined with longer curing periods. Conversely, the highest electrical resistivity was achieved in polypropylene-fiber mixtures with high fiber dosage and prolonged curing. Hybrid fiber systems provided a balanced combination of mechanical enhancement and electrical resistivity, indicating their potential suitability for multifunctional geopolymer composites.

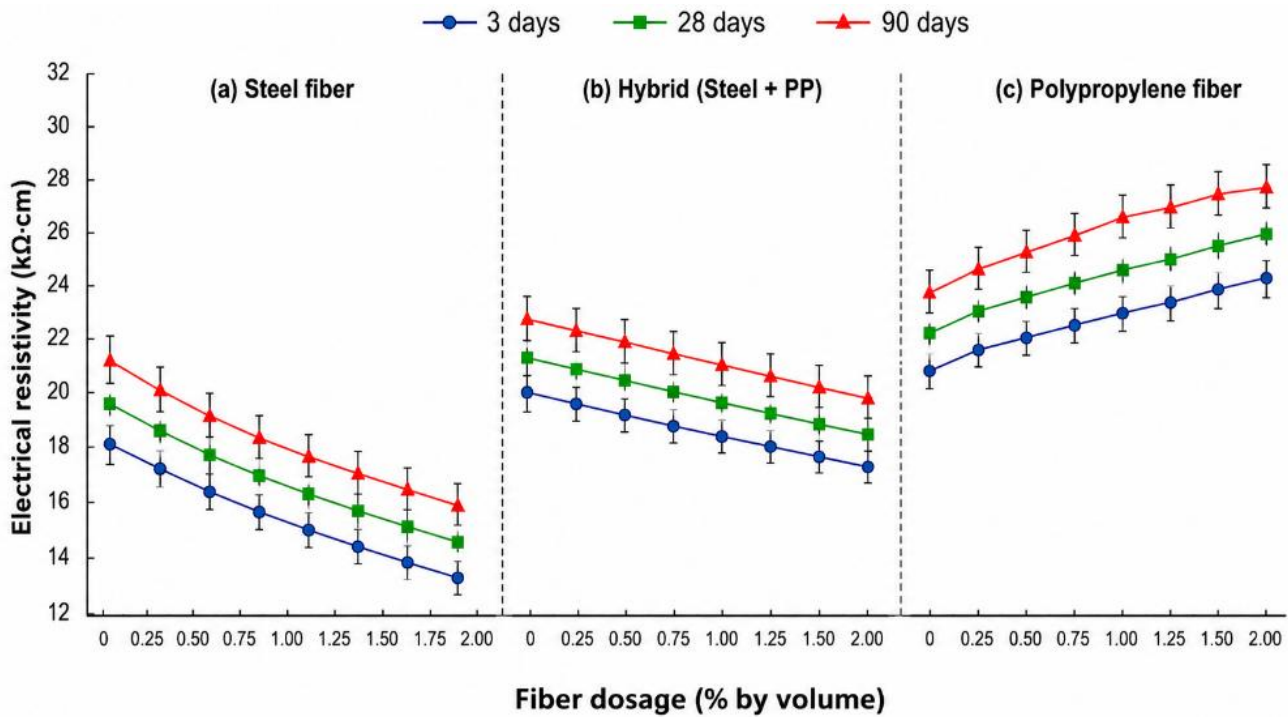


Figure 4. Electrical resistivity variation with fiber dosage, fiber type, and curing age

3.1. Machine learning modelling

The machine-learning analysis demonstrated that the selected input parameters were capable of predicting compressive strength, tensile strength, and electrical resistivity with high accuracy within the investigated experimental range. The input variables considered in the modelling process included fiber type, fiber dosage, and curing age. The target outputs were compressive strength, tensile strength, and electrical resistivity. Six regression algorithms were evaluated, namely Linear Regression (LR), Decision Tree (DT), Random Forest (RF), Gradient Boosting (GB), Support Vector Regression (SVR), and K-Nearest Neighbors Regression (KNN).

Because the experimental database contained a relatively limited number of observations, five-fold cross-validation was adopted to improve model reliability and reduce the risk of overfitting. Model performance was evaluated using the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE).

For compressive strength prediction, Linear Regression produced the highest predictive accuracy, achieving a cross-validated R^2 value of approximately 0.982, with an MAE of 1.176 MPa and an RMSE of 1.478 MPa. Gradient Boosting also showed strong predictive capability with an R^2 value close to 0.968. The excellent performance of relatively simple regression-based models indicates that compressive strength followed a highly systematic trend governed primarily by curing age

and fiber dosage. The inclusion of hybrid fiber mixtures slightly increased the nonlinear behavior of the dataset; however, the overall relationship remained sufficiently structured for accurate prediction.

For tensile strength prediction, Gradient Boosting achieved the best overall performance, with an R^2 value of approximately 0.958, an MAE of 0.162 MPa, and an RMSE of 0.197 MPa. Support Vector Regression and Linear Regression also demonstrated strong predictive performance. These results indicate that tensile strength was strongly dependent on fiber dosage and fiber type because fibers directly contributed to crack bridging and post-cracking resistance. Hybrid steel–polypropylene mixtures exhibited intermediate tensile-strength behavior, which improved the robustness of nonlinear learning models.

Electrical resistivity prediction was also successfully achieved using machine-learning approaches. Gradient Boosting provided the highest prediction accuracy, with an R^2 value of approximately 0.969, an MAE of 0.631 $k\Omega \cdot cm$, and an RMSE of 0.758 $k\Omega \cdot cm$. Compared with compressive and tensile strength, electrical resistivity exhibited more pronounced nonlinear and categorical behavior because of the fundamentally different electrical characteristics of steel and polypropylene fibers. Steel fibers reduced electrical resistivity because of their conductive nature, whereas polypropylene

fibers increased resistivity because of their insulating properties. Hybrid fiber systems produced intermediate resistivity responses, which were

effectively captured by the Gradient Boosting algorithm.

Table 5. Best cross-validated machine-learning performance for each target property

Target property	Best model	R ²	MAE	RMSE
Compressive strength (MPa)	Linear Regression	0.982	1.176 MPa	1.478 MPa
Tensile strength (MPa)	Gradient Boosting	0.958	0.162 MPa	0.197 MPa
Electrical resistivity (kΩ·cm)	Gradient Boosting	0.969	0.631 kΩ·cm	0.758 kΩ·cm

Feature-importance analysis obtained from the Gradient Boosting models showed strong agreement with the experimentally observed trends. For compressive strength, curing age was identified as the most influential parameter, with a relative importance value of approximately 0.566, followed by fiber dosage at 0.376 and fiber type at 0.058. This result confirms that geopolymerization and matrix densification continued progressively with curing time, resulting in increased compressive strength. For tensile strength, fiber dosage was the dominant variable, with a relative importance value of approximately 0.615, followed by curing age at

0.238 and fiber type at 0.147. This behavior reflects the direct role of fibers in resisting crack initiation and propagation. The hybrid fiber mixtures contributed to a more distributed crack pattern, which enhanced tensile resistance and ductility. For electrical resistivity, fiber type was identified as the dominant parameter, with an importance value of approximately 0.758, followed by fiber dosage at 0.143 and curing age at 0.099. This finding is physically meaningful because the conductive steel fibers and insulating polypropylene fibers fundamentally altered the electrical transport behavior of the geopolymer matrix.

Table 6. Gradient Boosting feature importance for each target property

Target property	Fiber type	Fiber dosage	Curing age
Compressive strength	0.058	0.376	0.566
Tensile strength	0.147	0.615	0.238
Electrical resistivity	0.758	0.143	0.099

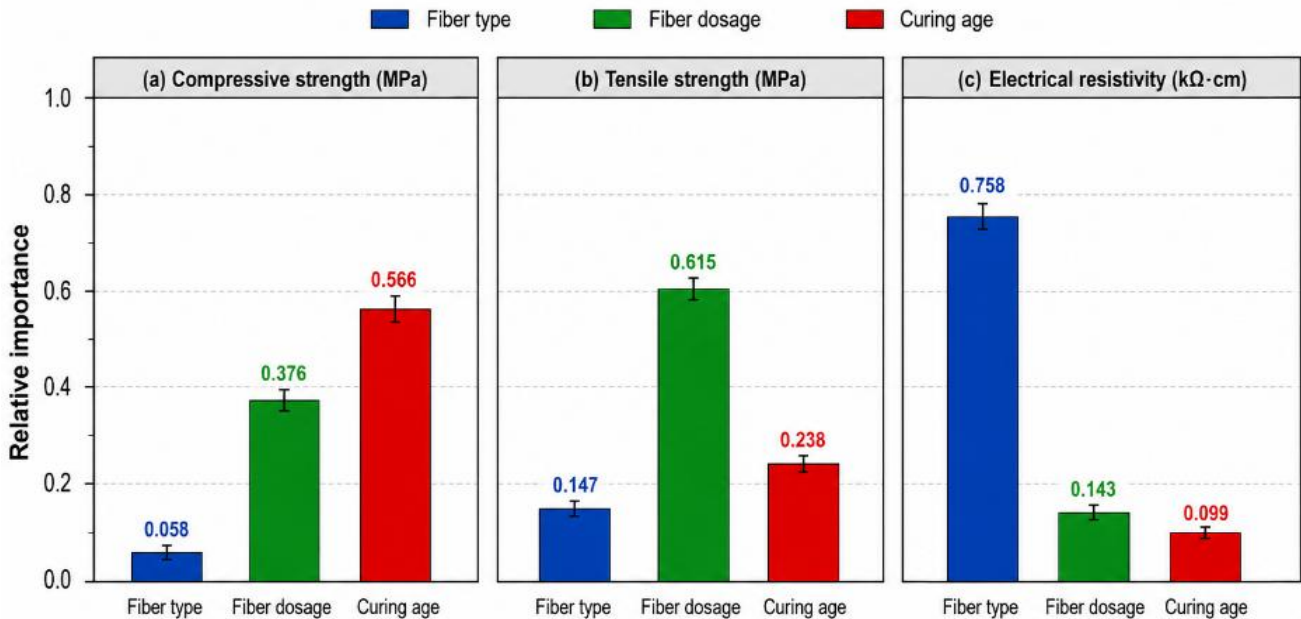


Figure 5. Relative feature importance obtained from Gradient Boosting models for the three target properties

Overall, the machine-learning models successfully captured physically meaningful relationships between the investigated variables and the measured properties. Curing age primarily controlled compressive-strength development because continued geopolymerization enhanced matrix densification with time. Fiber dosage exerted the greatest influence on tensile strength because fibers directly contributed to crack resistance and post-cracking behavior. Electrical resistivity was governed mainly by fiber type because of the contrasting electrical characteristics of steel and polypropylene fibers.

4. CONCLUSION

This study investigated the influence of steel fibers, polypropylene (PP) fibers, and hybrid steel–polypropylene fiber systems on the compressive strength, tensile strength, and electrical resistivity of geopolymer concrete activated with a 12 M sodium hydroxide solution. Based on the experimental and machine-learning analyses, the following conclusions can be drawn:

- The investigated geopolymer concrete mixtures exhibited compressive strengths ranging from 31.06 to 79.13 MPa, tensile strengths ranging from 3.02 to 7.15 MPa, and electrical resistivity values ranging from 14.84 to 29.97 $\text{k}\Omega\cdot\text{cm}$, demonstrating the significant influence of fiber type, dosage, and curing age on both mechanical and functional performance.
- Curing age strongly affected the development of geopolymer concrete properties. Mean compressive strength increased from 44.41 MPa at 3 days to 63.83 MPa at 90 days, while mean tensile strength increased from 4.19 MPa to 5.29 MPa over the same period. Electrical resistivity also increased with curing age, indicating progressive geopolymerization and matrix densification.
- Increasing fiber dosage improved both compressive and tensile strength. Across all mixtures, compressive strength increased from 41.99 MPa at 0% fiber dosage to 63.41 MPa at 2.0% fiber dosage, while tensile strength increased from 3.52 MPa to 5.85 MPa. This improvement was attributed to enhanced crack-bridging capability and improved resistance to crack propagation.

Despite the strong predictive performance, several limitations should be acknowledged. The dataset size remained relatively limited, and the sodium hydroxide molarity was maintained constant throughout the experimental program. Consequently, the developed models should be interpreted as reliable interpolation tools within the investigated experimental range rather than universal predictive models applicable to all geopolymer concrete systems. Future studies should incorporate larger experimental databases, additional mixture parameters, and external validation datasets to improve the generalization capability of the proposed machine-learning framework.

- Steel-fiber mixtures produced the highest mechanical performance because of the superior stiffness, bond characteristics, and crack-arresting ability of steel fibers. The average compressive and tensile strengths of steel-fiber mixtures reached 54.94 MPa and 4.99 MPa, respectively, compared with 50.14 MPa and 4.34 MPa for polypropylene-fiber mixtures.
- Polypropylene-fiber mixtures produced the highest electrical resistivity because of the nonconductive nature of polypropylene fibers. The average electrical resistivity of polypropylene-fiber mixtures reached 25.75 $\text{k}\Omega\cdot\text{cm}$, whereas steel-fiber mixtures exhibited a lower average resistivity of 18.22 $\text{k}\Omega\cdot\text{cm}$ because conductive steel fibers facilitated electrical transport within the matrix.
- Hybrid steel–polypropylene fiber mixtures provided balanced performance by combining improved mechanical strength with moderate electrical resistivity. The hybrid system demonstrated the potential to optimize both structural and durability-related characteristics simultaneously.
- The highest mechanical performance was achieved by the steel-fiber mixture containing 2.0% fiber at 90 days, which produced a compressive strength of 79.13 MPa and a tensile strength of 7.15 MPa. The highest electrical resistivity was obtained in the polypropylene-fiber mixture containing 1.75% fiber at 90 days, reaching 29.97 $\text{k}\Omega\cdot\text{cm}$.
- The machine-learning models demonstrated high predictive capability within the investigated experimental range. The best cross-validated R^2

values were approximately 0.982 for compressive strength, 0.958 for tensile strength, and 0.969 for electrical resistivity. These results indicate that the selected input variables were sufficient to capture the dominant trends governing material behavior.

- Feature-importance analysis revealed that curing age was the most influential parameter affecting compressive strength, fiber dosage was the dominant factor controlling tensile strength, and fiber type had the greatest influence on electrical resistivity. These findings were consistent with

the experimentally observed physical mechanisms.

Overall, the results demonstrate that the performance of fiber-reinforced geopolymer concrete is governed by the coupled interaction of fiber type, fiber dosage, hybridization strategy, and curing age. Steel fibers are highly effective for improving mechanical strength, whereas polypropylene fibers are advantageous for increasing electrical resistivity and durability-related performance. Hybrid fiber systems provide a promising approach for achieving a balanced combination of structural and functional properties.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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